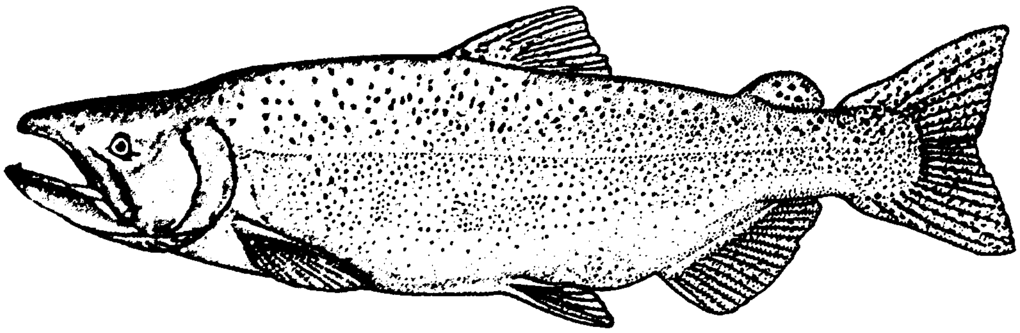
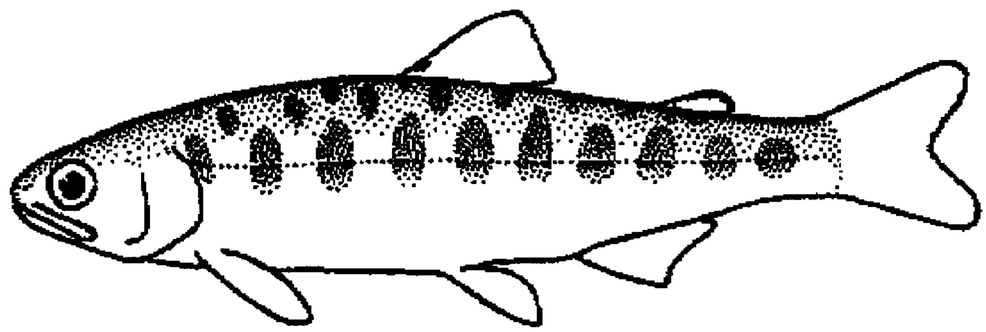
MONITORING OF THE PHASE 3A RESTORATION PROJECT IN CLEAR CREEK USING 2-DIMENSIONAL MODELING METHODOLOGY





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PREFACE

This report is part of the Clear Creek Restoration Project Monitoring Investigations, a 3-year effort which began April 1999. Title 34, section 3406(b)(12) of the Central Valley Project Improvement Act, P.L. 102-575, authorized funding for channel restoration of Clear Creek to provide spawning, incubation, and rearing habitat for salmon and steelhead. The purpose of this investigation is to evaluate the success of these restoration activities with regards to changing the amount of fall-run Chinook salmon spawning and rearing habitat.

To those who are interested, comments and information regarding this program and the habitat resources of Central Valley rivers are welcomed. Written comments or information can be submitted to:

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INTRODUCTION

The decline of spring and fall-run Chinook salmon and steelhead trout in Clear Creek over the last decade is attributed to many factors including habitat degradation (Yoshiyama *et al.*, 1998; Yoshiyama *et al.*, 2000). Clear Creek's existing habitat appears inadequate for either spawning or rearing. The Central Valley Project Improvement Act (CVPIA), section 3406(b)(12), authorized funding for channel restoration of Clear Creek to provide spawning, incubation, and rearing habitat for salmon and steelhead. In response to this authorization, in 1998 the U.S. Fish and Wildlife Service (Service) developed the Lower Clear Creek Flood Plain Restoration Project to increase spawning success on the section of Clear Creek downstream of Saeltzer Dam. Part of this study proposal included utilizing 2-D modeling and the Service's Instream Flow Incremental Methodology (IFIM), to compare total weighted usable area (WUA) of salmonid habitat before and after channel restoration. The Clear Creek Study is a 3-year effort originally designed to be completed in two phases (pre-restoration and post-restoration). A final report for the first phase (USFWS 2005b), presenting findings from the pre-restoration and the post-restoration plan, was completed in February 2005. This second study report for the Clear Creek Restoration Project is concerned with an evaluation of post-restoration effects in Phase 3A, the first in-channel portion of the restoration. Additional reports will be issued addressing future phases of the restoration project as they are constructed.

A 2-D hydraulic and habitat model (RIVER2D) was used for predicting WUA, instead of the Physical Habitat Simulation (PHABSIM[1]) component of the IFIM. 2-D model inputs include the bed topography and bed roughness, and the water surface elevation at the downstream end of the site. The amount of habitat present in the site is computed using the depths and velocities predicted by the 2-D model, and the substrate and cover present in the site. The 2-D model avoids problems of transect placement, since data is collected uniformly across the entire site. The 2-D model also has the potential to model depths and velocities over a range of flows more accurately than PHABSIM because it takes into account upstream and downstream bed topography and bed roughness, and explicitly uses mechanistic processes (conservation of mass and momentum), rather than Manning's Equation and a velocity adjustment factor (Leclerc et al. 1995). Other advantages of 2-D modeling are that it can explicitly handle complex hydraulics, including transverse flows, across-channel variation in water surface elevations, and flow contractions/expansions (Ghanem et al. 1996, Crowder and Diplas 2000, Pasternack et al. 2004). With appropriate bathymetry data, the model scale is small enough to correspond to the scale of microhabitat use data with depths and velocities produced on a continuous basis, rather than in discrete cells. The 2-D model, with compact cells, should be more accurate than PHABSIM, with long rectangular cells, in capturing longitudinal variation in depth, velocity, substrate and

[1] PHABSIM is the collection of one dimensional hydraulic and habitat models which are used to predict the relationship between physical habitat availability and streamflow over a range of river discharges.

cover. The 2-D model should do a better job of representing patchy microhabitat features, such as gravel patches. The data can be collected with a stratified sampling scheme, with higher intensity sampling in areas with more complex or more quickly varying microhabitat features, and lower intensity sampling in areas with uniformly varying bed topography and uniform substrate. The 2-D model is more efficient for modeling juvenile habitat than PHABSIM, since it allows for intensive sampling on the stream margins, where most juvenile habitat is located, and less-intensive sampling in the middle of the river, which tends to have velocities which are too high for juvenile salmon. Bed topography and substrate mapping data can be collected at a very low flow, with the only data needed at high flow being water surface elevations at the up- and downstream ends of the site and flow and edge velocities for validation purposes. In addition, alternative habitat suitability criteria, such as measures of habitat diversity, can be used.

METHODS

Transect Placement (post-restoration study site setup)

The Phase 3A post-restoration study site, encompassing the entire restored channel, was established in January 2003. The site also included a large off-channel area (a remnant of the pre-restoration channel) just downstream of the post-restoration channel. As a result, there were three portions of the study site: the post-restoration area, the off-channel area, and a pre-restoration area (at the bottom of the study site). The site had a length of 1,199 feet, an average width of 176 feet, and a mean site bed slope of 0.35%. Two transects were placed in the site, one at the upstream end of the restoration area and one a short distance downstream of the downstream end. The downstream transect was modeled with PHABSIM to provide water surface elevations as an input to the 2-D model. Calibration of the 2-D model was done using data from the upstream transect. This calibration is accomplished by adjusting the bed roughness until the water surface elevation at the upstream end of the site matches the water surface elevation predicted by PHABSIM. The 2-D model uses as inputs the bed topography, cover, and substrate of a site and the water surface elevation at the downstream end of the site, to predict the amount of habitat present in the site. Transect pins (headpin and tailpins) were marked on each river bank above the 1,500 cfs level using rebar driven into the ground. Survey flagging and spray paint were used to mark the locations of each pin.

Hydraulic and Structural Habitat Data Collection

Vertical benchmarks were established to serve as the reference elevation to which all elevations (streambed and water surface) were tied. In addition, horizontal benchmarks were established to serve as reference locations to which all horizontal locations (northings and eastings) were tied. Fluvial geomorphologists for the restoration project established total station control points previous to the start of our IFIM work. Our vertical and horizontal benchmarks were tied into these points.

The data collected at the upstream (transect 2) and downstream (transect 1) transects include: 1) water surface elevations (WSELs), measured to the nearest .01 foot at five different stream discharges using standard surveying techniques (differential leveling); 2) streambed elevations determined by subtracting the measured depth from the surveyed WSEL at a measured flow; 3) dry ground elevations to points above bankfull discharge surveyed to the nearest 0.1 foot; 4) mean water column velocities measured at the points where bed elevations were taken; and 5) substrate and cover classification at these same locations and also where dry ground elevations were surveyed. Table 1 gives the substrate codes and size classes used in this study. Table 2 gives the cover codes and categories used in this study.

Table 1
Substrate Descriptors and Codes

Code	Type	Particle Size (inches)
0.1	Sand/Silt	< 0.1
1	Small Gravel	0.1 – 1
1.2	Medium Gravel	1 – 2
1.3	Medium/Large Gravel	1 – 3
2.3	Large Gravel	2 – 3
2.4	Gravel/Cobble	2 – 4
3.4	Small Cobble	3 – 4
3.5	Small Cobble	3 – 5
4.6	Medium Cobble	4 – 6
6.8	Large Cobble	6 – 8
8	Large Cobble	8 – 10
9	Boulder/Bedrock	> 12
10	Large Cobble	10 – 12

We collected the data between the upstream and downstream transects by obtaining the bed elevation and horizontal location of individual points with a total station, while the cover and substrate were visually assessed at each point. These parameters were collected at enough points to characterize the bed topography, substrate and cover of the site. There were 83 points collected on transects and 1,439 points collected between the transects, with a density of 7.77

Table 2
Cover Coding System

Cover Category	Cover Code
No cover	0
Cobble	1
Boulder	2
Fine woody vegetation (< 1" diameter)	3
Fine woody vegetation + overhead	3.7
Branches	4
Branches + overhead	4.7
Log (> 1' diameter)	5
Log + overhead	5.7
Overhead cover (> 2' above substrate)	7
Undercut bank	8
Aquatic vegetation	9
Aquatic vegetation + overhead	9.7
Rip-rap	10

points/100 m^2 overall. Substrate and cover along the transects were also determined visually. To validate the velocities predicted by the 2-D model, velocity measurements were collected by wading with a wading rod equipped with a Marsh-McBirney^R model 2000 velocity meter or a Price AA velocity meter equipped with a current meter digitizer at the low flow[2]. These points were distributed in a uniform manner throughout the entire study site; however the exact location was random . These validation velocities and the velocities measured on the transects described previously were collected at 0.6 of the depth for 20 seconds. The horizontal locations and bed elevations were determined by taking a total station shot on a prism held at each point where depth and velocity were measured. A minimum of 50 representative points were measured.

[2] Depth, substrate and cover measurements were also collected at these locations.

Hydraulic and structural data collection began in January 2003 and was completed in August 2003. Water surface elevations were collected at five flows (96, 188/189[3], 259, 326[4] and 1446 cfs). Data collection was difficult at times because some areas were too deep at certain flows to get measurements and yet the creek is too small to allow for the use of a jet boat. Discharge measurements were collected at all five flow levels while wading with a wading rod equipped with a Marsh-McBirney[R] model 2000 velocity meter or a Price AA velocity meter equipped with a current meter digitizer.

Hydraulic Model Construction and Calibration

All data were compiled and checked before entry into PHABSIM[5] data files. A lookup table of substrate and cover ranges/values was created to determine the substrate and cover for each vertical (e.g., if the substrate size class was 2-4 inches on a transect from station 50 to 70, all of the verticals with station values between 50 and 70 were given a substrate coding of 2.4). Dry bed elevation data in field notebooks were entered into the spreadsheet to extend the bed profile up the banks above the WSEL of the highest measured flow. An ASCII file produced from the spreadsheet was run through the FLOMANN program (written by Andy Hamilton, USFWS) to get the PHABSIM input file and then translated into RHABSIM[6] files.

A total of four sets of measured WSELs were used, all being checked to ensure that there was no uphill movement of water. Calibration flows in the data files (Appendix A) were the flows measured, which included the entire flow of Clear Creek. The slope for each transect was computed at each measured flow as the difference in WSELs between the two transects divided by the distance between the two. The slope used for each transect was calculated by averaging the slopes computed for each flow.

The stage of zero flow (SZF), an important parameter used in calibrating the stage-discharge relationship, was determined for each transect and entered. In habitat types without backwater effects (e.g., riffles and runs), this value generally represents the lowest point in the streambed across a transect. However, if the upstream transect contains a lower bed elevation than the

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[3] Water surface elevations were measured at the upstream transect on June 3 (188 cfs) and at the downstream transect on June 5 (189 cfs).

[4] The 326 cfs flow data was not used in further analyses when it was later discovered that the flow was increasing during the time period measurements were being taken on the transects.

[5] While the 2-D model is used to predict depth and velocity throughout the study reach, the PHABSIM model was used to establish the boundary conditions for the 2-D model.

[6] RHABSIM is a commercially-produced software (Payne and Associates 1998) that incorporates the modeling procedures used in PHABSIM.

downstream transect, the SZF for the downstream transect applies to both. For the Phase 3A post-restoration site, where the hydraulic control for the upstream transect was located within the site, the SZF (the thalweg elevation at the hydraulic control) was determined from the bed topography data collected for the 2-D model.

The first step in the calibration procedure was to determine the best approach for WSEL simulation. Initially, the *IFG4* hydraulic model (Milhous *et al.*, 1989) was run on the PHABSIM file to compare predicted and measured WSELs. This model produces a stage-discharge relationship using a log-log linear rating curve calculated from at least three sets of measurements taken at different flows. Besides *IFG4*, two other hydraulic models are available in PHABSIM to predict stage-discharge relationships. These models are: 1) *MANSQ*, which operates under the assumption that the geometry of the channel and the nature of the streambed controls WSELs; and 2) *WSP*, the water surface profile model, which calculates the energy loss between transects to determine WSELs. *MANSQ*, like *IFG4*, evaluates each transect independently. *WSP* must, by nature, link at least two adjacent transects. *IFG4,* the most versatile of these models, is considered to have worked well if the following criteria are met: 1) the beta value (a measure of the change in channel roughness with changes in streamflow) is between 2.0 and 4.5; 2) the mean error in calculated versus given discharges is less than 10%; 3) there is no more than a 25% difference for any calculated versus given discharge; and 4) there is no more than a 0.1 foot difference between measured and simulated WSELs[7]. *MANSQ* is considered to have worked well if the second through fourth of the above criteria are met, and if the beta value parameter used by *MANSQ* is within the range of 0 to 0.5. The first *IFG4* criterion is not applicable to *MANSQ*. *WSP* is considered to have worked well if the following criteria are met: 1) the Manning's n value used falls within the range of 0.04 - 0.07; 2) there is a negative log-log relationship between the reach multiplier and flow; and 3) there is no more than a 0.1 foot difference between measured and simulated WSELs. The first three *IFG4* criteria are not applicable to *WSP*.

IFG4 met the above criteria (Appendix A) for the upstream transect, and for the three highest flows for the downstream transect. *MANSQ* worked successfully for the lower two flows in the downstream transect, meeting the above criteria for *MANSQ* (Appendix A). The final step in simulating WSELs was to check whether water was going uphill at any of the simulated WSELs. This did not occur.

Velocity Adjustment Factors (VAFs) were examined for all of the simulated flows (Appendix B). Neither of the post-restoration study site transects deviated significantly from the expected pattern of VAFs. In addition, VAF values (ranging from 0.36 to 3.69) were all within an acceptable range of 0.2 to 5.0.

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[7] The first three criteria are from U.S. Fish and Wildlife Service (1994), while the fourth criterion is our own.

The total station data and the PHABSIM transect data were combined in Excel to create the input files (bed, substrate and cover) for the 2-D modeling program. An artificial extension one channel-width-long was added upstream of the top of the site to enable the flow to be distributed by the model when it reached the study area.

The bed files contain the horizontal location (northing and easting), bed elevation and initial bed roughness value for each point, while the substrate and cover files contain the horizontal location, bed elevation and, respectively, the substrate and cover code for each point. The initial bed roughness value for each point was determined from the substrate and cover codes for that point and the corresponding bed roughness values in Table 3, with the bed roughness value computed as the sum of the substrate bed roughness value and the cover bed roughness value. The bed roughness values for substrate in Table 3 were computed as five times the average particle size[8]. The bed roughness values for cover in Table 3 were computed as five times the average cover size, where the cover size was measured on the Sacramento River on a representative sample of cover elements of each cover-type. The bed, substrate and cover files were exported from Excel as ASCII files.

A utility program, R2D_BED (Steffler 2001b), was used to define the study area boundary and to refine the raw topographical data TIN (triangulated irregular network) by defining breaklines[9] going up the channel along features such as thalwegs, tops of bars and bottoms of banks. Breaklines were also added along lines of constant elevation. The bed topography is shown in Appendix C.

An additional utility program, R2D_MESH (Steffler 2001a), was used to define the inflow and outflow boundaries and create the finite element computational mesh for the River2D model. R2D_MESH uses the final bed file as an input. The first stage in creating the computational mesh was to define mesh breaklines[10] which coincided with the final bed file breaklines. Additional mesh breaklines were then added between the initial mesh breaklines, and then additional nodes were added as needed to improve the fit between the mesh and the final bed file

[8] Five times the average particle size is approximately the same as 2 to 3 times the d85 particle size, which is recommended as an estimate of bed roughness height (Yalin 1977).

[9] Breaklines are a feature of the R2D_Bed program which force the TIN of the bed nodes to linearly interpolate bed elevation and bed roughness values between the nodes on each breakline and force the TIN to fall on the breaklines (Steffler 2001b).

[10] Mesh breaklines are a feature of the R2D_MESH program which force edges of the computation mesh elements to fall on the mesh breaklines and force the TIN of the computational mesh to linearly interpolate the bed elevation and bed roughness values of mesh nodes between the nodes at the end of each breakline segment (Steffler 2001a). A better fit between the bed and mesh TINs is achieved by having the mesh and bed breaklines coincide.

Table 3
Initial Bed Roughness Values[11]

Substrate Code	Bed Roughness (m)	Cover Code	Bed Roughness (m)
0.1	0.05	0.1	0
1	0.1	1	0
1.2	0.2	2	0
1.3	0.25	3	0.11
2.3	0.3	3.7	0.2
2.4	0.4	4	0.62
3.4	0.45	4.7	0.96
3.5	0.5	5	1.93
4.6	0.65	5.7	2.59
6.8	0.9	7	0.28
8	1.25	8	2.97
9	0.05	9	0.29
10	1.4	9.7	0.57
		10	3.05

and to improve the quality of the mesh, as measured by the Quality Index (QI) value. An ideal mesh (all equilateral triangles) would have a QI of 1.0. A QI value of at least 0.2 is considered acceptable (Steffler 2001a). The QI is a measure of how much the least equilateral mesh element deviates from an equilateral triangle. The study site mesh had a QI value of 0.31. In addition, the difference in bed elevation between the mesh and final bed file was less than 0.1 foot (0.03 m) for 76% of the nodes. In most cases, the portions of the mesh where there was greater than a 0.1 foot (0.03 m) difference between the mesh and final bed file were in steep areas; in these areas, the mesh would be within 0.1 foot (0.03 m) vertically of the bed file within 1.0 foot (0.3 m) horizontally of the bed file location. Given that we had a 1-foot (0.3 m) horizontal level of

[11] For substrate code 9, we used bed roughnesses of 0.71 and 1.95, respectively, for cover codes 1 and 2. Bed roughnesses of zero were used for cover codes 1 and 2 for all other substrate codes, since the roughness associated with the cover was included in the substrate roughness.

accuracy, such areas would have an adequate fit of the mesh to the bed file. The number of nodes was 15,234. The final step with the R2D_MESH software was to generate the computational (cdg) file.

The cdg file was opened in the RIVER2D software, where the computational bed topography mesh was used together with the WSEL at the bottom of the site, the flow entering the site, and the bed roughnesses of the computational mesh elements to compute the depths, velocities and WSELs throughout the site. The basis for the current form of RIVER2D is given in Ghanem et al (1995). The computational mesh was run to steady state at the highest flow to be simulated, 900 cfs (25.5 m^3/s), and the WSELs predicted by RIVER2D at the upstream end of the site were compared to the WSELs predicted by PHABSIM at the upstream transect. The bed roughnesses of the computational mesh elements were then modified by multiplying them by a constant bed roughness multiplier (BR Mult) until the WSELs predicted by RIVER2D at the upstream end of the site matched the WSELs predicted by PHABSIM at the top transect.

A stable solution will generally have a solution change (Sol Δ) of less than 0.00001 and a net flow (Net Q) of less than 1% (Steffler and Blackburn 2001). In addition, solutions for low gradient streams should usually have a maximum Froude Number (Max F) of less than one[12]. Finally, the WSEL predicted by the 2-D model should be within 0.1 foot (0.031 m) of the WSEL measured at the upstream transects[13]. The calibrated cdg file had a solution change of less than 0.000001, with a net Q of 0.47 %. The calibrated cdg file had a maximum Froude Number of 2.99 (Appendix D). We considered the solution to be acceptable since the Froude Number only exceeded one at a few nodes, with the vast majority of the site having Froude Numbers less than one. A high Froude Number at a very limited number of nodes would be expected to have an insignificant effect on the model results. The calibrated cdg file WSEL for the upstream transect was 0.12 feet (0.035 m) higher than the measured WSEL generated by PHABSIM at 900 cfs. Measured WSELs at 1,446 cfs, the highest flow at which measurements were taken, varied by greater than 0.1 foot between the left (south) and right (north) banks, with the right bank WSEL 0.08 feet higher than the average WSEL at that flow. If at 900 cfs the right bank is .06 feet higher than the average WSEL taken along the transect this would bring the simulated right bank WSEL within 0.1 foot of the measured value from PHABSIM.

Velocity validation is the final step in the preparation of the hydraulic models for use in habitat simulation. Velocities predicted by RIVER2D were compared with measured velocities to determine the accuracy of the model's predictions of mean water column velocities. The

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[12] This criterion is based on the assumption that flow in low gradient streams is usually subcritical, where the Froude number is less than one (Peter Steffler, personal communication).

[13] We have selected this standard because it is a standard used for PHABSIM (U. S. Fish and Wildlife Service 2000).

measured velocities used were both those measured at the up- and downstream transects and the 50 measurements taken between the transects. See Appendix E for velocity validation statistics. Although there was a strong correlation between predicted and measured velocities, there were significant differences between individual measured and predicted velocities. In general, the simulated and measured cross-channel velocity profiles at the up- and downstream transects (Appendix E[14]) were relatively similar in shape. Differences in magnitude in most cases are likely due to (1) aspects of the bed topography of the site that were not captured in our data collection, (2) the effect of the velocity distribution at the upstream boundary of the site, (3) operator error during data collection, i.e., the probe was not facing precisely into the direction of current, and (4) range of natural velocity variation at each point over time resulting in some measured data points at the low or high end of the velocity range averaged in the model simulations.

River2D distributes velocities across the upstream boundary in proportion to depth, so that the fastest velocities are at the thalweg. In contrast, the bed topography of a site may be such that the fastest measured velocities may be located in a different part of the channel. Since we did not measure the bed topography upstream of the site, this may result in River2D improperly distributing the flow across the upstream end of the site. As discussed above, we added an artificial upstream extension to the site to try to address this issue.

The 2-D model integrates effects from the surrounding elements at each point. Thus, point measurements of velocity can differ from simulated values simply due to the local area integration that takes place. As a result, the area integration effect noted above will produce somewhat smoother cross-channel velocity profiles than the observations.

Overall, the simulated velocities for the site were relatively similar to the measured velocities for both cross sections, with some differences in magnitude that fall within the expected amount of natural variation in velocity. The relationship is especially close for cross section one. Simulated velocities on the south side of cross section two, higher than the measured velocities, can likely be attributed to a boulder or other feature blocking flow upstream of the study site, resulting in the zero measured velocity value. The feature blocking the flow likely diverted additional flow along the south bank, resulting in the first measured velocity along that bank being higher than the simulated value. As bed topography data was not collected upstream of the study site any such features are not included in the model. Also, judging by the variation in the profile of the measured velocities along cross section two, this area was more hydraulically complex than cross section one. The model tended to smooth this pattern as described above.

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[14] Velocities were plotted versus northing, since the transects were orientated primarily north-south.

The flow and downstream WSEL in the calibrated cdg file were changed to simulate the hydraulics of the site at the simulation flows (50 cfs to 300 cfs by 25 cfs increments and 300 cfs to 900 cfs by 50 cfs increments). The cdg file for each flow contained the WSEL predicted by PHABSIM at the downstream transect at that flow. Each cdg file was run in RIVER2D to steady state. Again, a stable solution will generally have a Sol Δ of less than 0.00001 and a Net Q of less than 1%. In addition, solutions should usually have a Max F of less than one. The production cdg files all had a solution change of less than 0.00001, but the net Q was greater than 1% for 13 flows (Appendix F). We still considered these sites to have a stable solution since the net Q was not changing and the net Q in all cases was less than 5%. In comparison, the accepted level of accuracy for USGS gages is generally 5%. Thus, the difference between the flows at the upstream and downstream boundary (net Q) is within the same range as the accuracy for USGS gages, and is considered acceptable. The maximum Froude Number was greater than one for all of the simulated flows (Appendix F); however, we considered these production runs to be acceptable since the Froude Number was only greater than one at a few nodes, with the vast majority of the area within the site having Froude Numbers less than one.

Habitat Suitability Criteria (HSC) Development

The HSC for fall-run Chinook salmon spawning and fry and juvenile rearing used in this study were those developed from Sacramento River data. See U.S. Fish and Wildlife Service (2003) and (2005a) for details.

Biological Validation

We compared the combined habitat suitability predicted by RIVER2D at each redd location in the post-restoration site in 2003. We ran the RIVER2D cdg file for the post-restoration site at 287 cfs (the average flow at the restoration site for the fall-run spawning period, Oct 15 – Nov 14, 2003) to determine the combined habitat suitability at individual points for RIVER2D.

We obtained polygons of redd areas for fall-run Chinook salmon in 2003 from the Service's Red Bluff Fish and Wildlife Office. We assumed that the smallest polygons were one redd – based on this assumption, we calculated an average redd size of 211 ft^2. We then calculated how many redds were in the larger polygons by dividing each polygon area by the above average redd size. Based on this analysis, we came up with a total of 79 fall-run Chinook salmon redds in the restoration site in 2003. To establish the horizontal location (northing and easting) of each redd, we placed a point in the center of each of the smallest polygons and placed a point for each redd in the larger polygons, with the points equally spaced.

We used the above horizontal location for each redd to determine the location of each redd in the RIVER2D post-restoration site. We used a random-number generator to select 800 locations without redds in the RIVER2D site. Locations were eliminated that: 1) were less than 3 feet from a previously-selected location; 2) were less than 3 feet from a redd; 3) were not located in the wetted part of the site; and 4) were located in the in the upstream extension of the file, rather than in the site. We used a Mann-Whitney U test (Zar 1984) to determine whether the compound suitability predicted by RIVER2D was higher at redd locations versus locations where redds were absent.

Habitat Simulation

The final step was to simulate available habitat within the site for fall-run chinook salmon spawning and fry and juvenile rearing. Preference curve files for spawning and rearing were created containing the digitized HSC developed for the Sacramento River fall-run Chinook salmon (Appendix G). Separate substrate and cover files for the pre-restoration, post-restoration and off-channel area portions of the study site were created. RIVER2D was used with the final cdg files, the substrate files and the preference curve file to compute spawning WUA over the desired range of flows (50 cfs to 300 cfs by 25 cfs increments and 300 cfs to 900 cfs by 50 cfs increments) for each portion of the site. This process was repeated to compute the fry and juvenile rearing WUA using RIVER2D with the final cdg files, the cover files and the fry and juvenile rearing preference file, with the addition of a final step using an ArcMap post-processor to incorporate the adjacent velocity criteria. The fall-run Chinook salmon adult spawning and fry and juvenile rearing WUA values calculated are contained in Appendix G.

RESULTS

Biological Validation

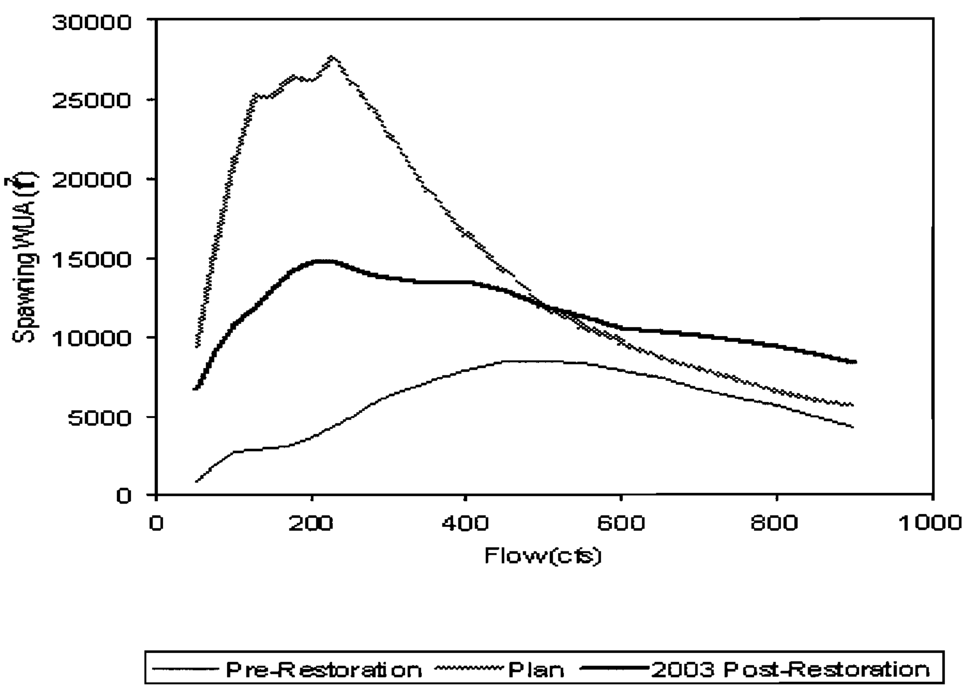
The combined habitat suitability predicted by the 2-D model was significantly higher for locations with redds (median = 0.13, n = 79) than for locations without redds (median = 0, n = 800), based on the Mann-Whitney U test ($p<0.000001$). The frequency distribution of combined habitat suitability for locations with redds is shown in Figure 1, while the frequency distribution of combined habitat suitability for locations without redds is shown in Figure 2. A greater number in the suitability index indicates greater suitability.

The location of redds relative to the distribution of combined suitability is shown in Appendix H. The 2-D model predicted that 9 of the 79 (11%) redd locations had a combined suitability of zero. Two had a combined suitability of zero due to the predicted substrate being too small (substrate codes of 0.1 and 1), one had a combined suitability of zero due to the predicted velocity being too low (less than 0.32 ft/s), four had a combined suitability of zero due to the predicted velocity being too fast (greater than 5.79 ft/s), and two had a combined suitability of zero due to the predicted depth being too low (depth less than 0.5 ft).

Habitat Simulation

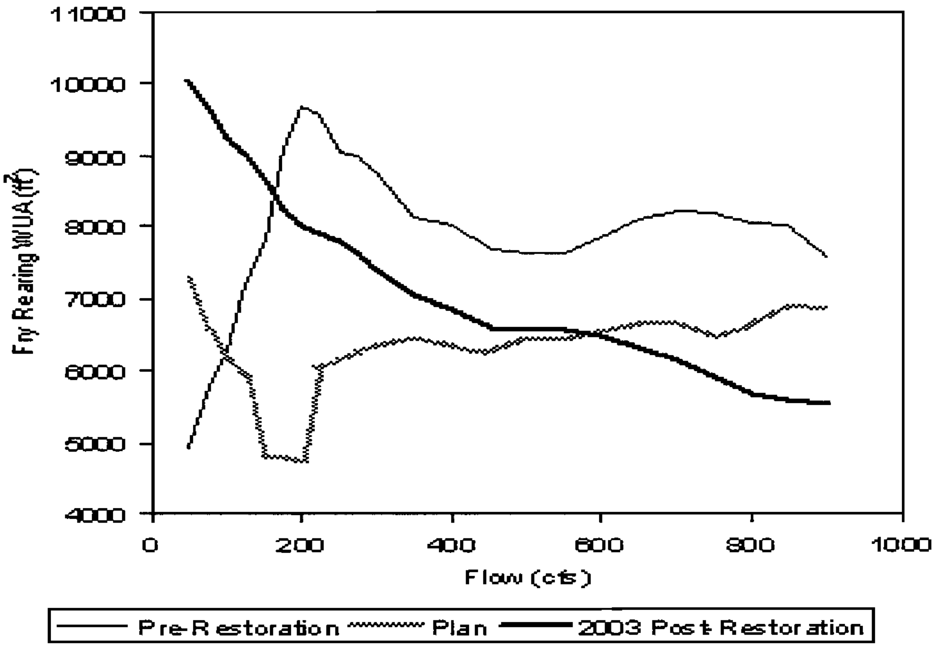
The flow habitat relationships for fall-run Chinook salmon spawning in the pre-restored, plan and restored Phase 3A project are shown in Figure 3. These results indicate that the plan and restored channel resulted in a significant increase in fall-run chinook salmon spawning habitat at all flows, as compared to the pre-restoration conditions, and that the flow with the maximum WUA will shift from 500 cfs under the pre-restoration conditions to 225 cfs and 550 cfs respectively under the plan and post-restoration channel. At the current spawning flows of 200 cfs, we modeled a 302% increase in spawning habitat due to the restoration project.

Figure 3
Fall-run Chinook Salmon Spawning Flow-Habitat Relationships



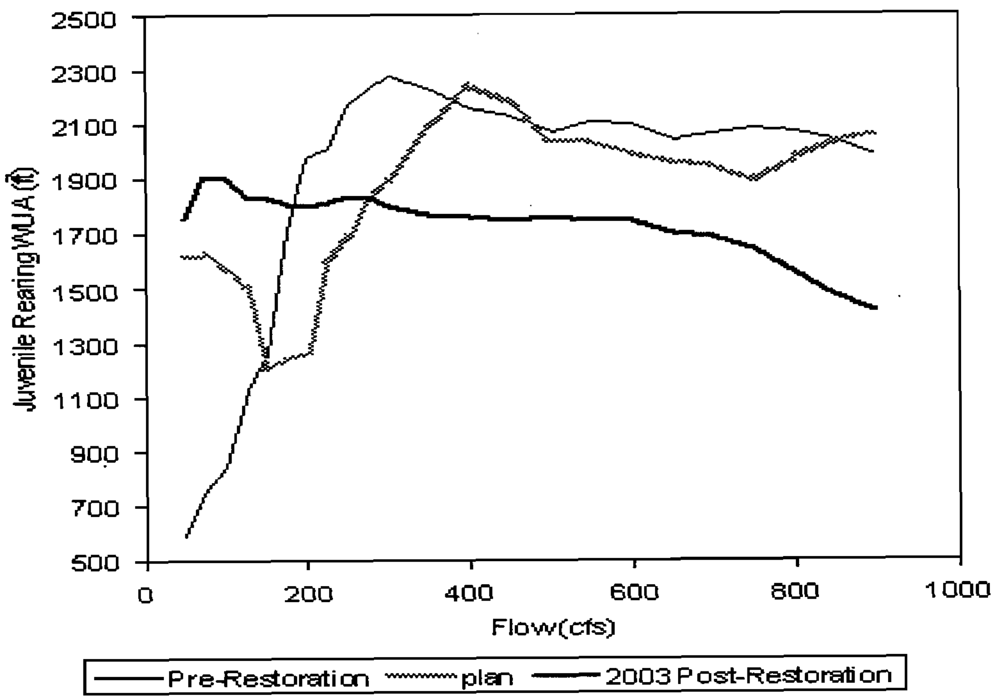
The flow habitat relationships for fall-run Chinook salmon fry rearing in the pre-restored, plan and restored Phase 3A project are shown in Figure 4. These results indicate that the post-restoration plan resulted in a significant increase in fall-run Chinook salmon fry rearing habitat at flows ≤ about 150 cfs, but a decrease in fry rearing at higher flows, as compared to the pre-restoration conditions. Conditions at the higher flows would undoubtedly be improved by augmenting existing cover with features such as more large woody debris and small alcoves, which have high suitability for fry rearing, into the restoration site. These features could also be included into plans for future restoration projects.

Figure 4
Fall-run Chinook Salmon Fry Flow-Habitat Relationships



The flow habitat relationships for fall-run Chinook salmon juvenile rearing in the pre-restored, plan and restored Phase 3A project are shown in Figure 5. As with the fry-rearing habitat, these results indicate that the post-restoration plan resulted in a significant increase in fall-run Chinook salmon juvenile rearing habitat at flows ≤ about 200 cfs, but a decrease in juvenile habitat at higher flows, as compared to the pre-restoration conditions. As is the case for the fry, the latter effect upon juvenile habitat would probably be alleviated by the augmentation of existing cover with features such as more large woody debris and small alcoves.

Figure 5
Fall-run Chinook Salmon Juvenile Flow-Habitat Relationships



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APPENDIX A
RHABSIM WSEL CALIBRATION

Calibration Methods and Parameters Used

XS #	Flow Range	Calibration Flows	Method	Parameters
1	50-150	96, 189	MANSQ	$\beta = 0.04$, CALQ = 189
1	150-900	189, 259, 1446	IFG4	- - -
2	50-900	96, 189, 259, 1446	IFG4	- - -

	BETA	%MEAN	Calculated vs Given Disch. (%)		Difference (measured vs. pred.)	
XS	COEFF.	ERROR	96	189	96	189
1	----	0	0	0	0.00	0.00

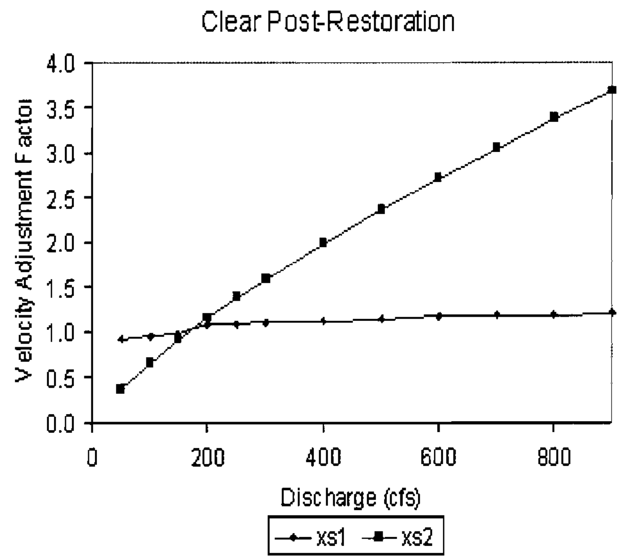
	BETA	%MEAN	Calculated vs Given Disch. (%)			Difference (measured vs. pred.)		
XS	COEFF.	ERROR	189	259	1446	189	259	1446
1	2.40	7.03	9.48	11.14	0.6	0.09	0.10	0.01

	BETA	%MEAN	Calculated vs Given Disch. (%)				Difference (measured vs. pred.)			
XS	COEFF.	ERROR	96	189	259	1446	96	189	259	1446
2	3.10	4.81	5.4	10.24	3.52	0.61	0.03	0.05	0.02	0.01

APPENDIX B
VELOCITY ADJUSTMENT FACTORS

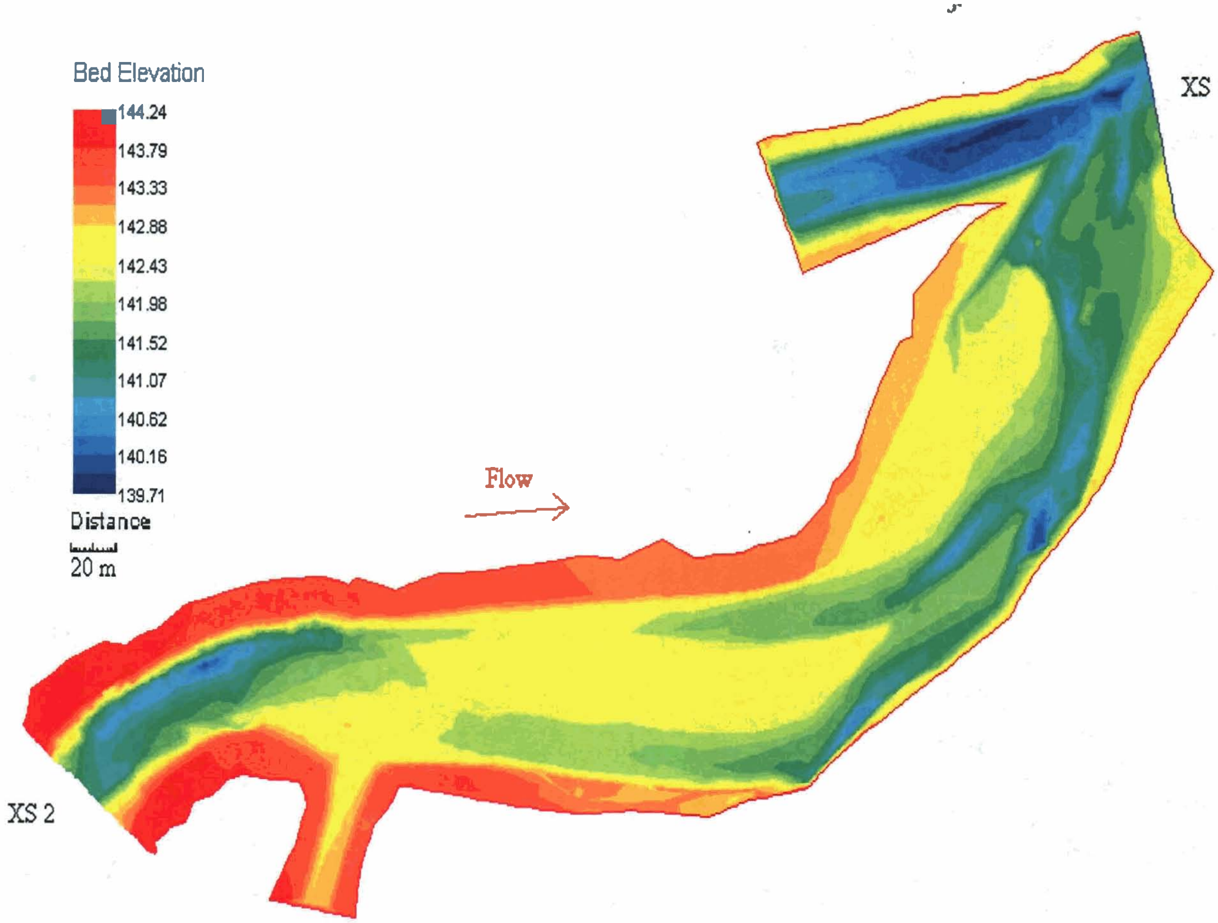
Post Restoration Study Site

Velocity Adjustment Factors		
Discharge	Xsec 1	Xsec 2
50	0.92	0.36
100	0.95	0.65
150	0.97	0.91
200	1.09	1.15
250	1.09	1.38
300	1.10	1.59
400	1.12	1.99
500	1.14	2.37
600	1.16	2.72
700	1.18	3.06
800	1.19	3.38
900	1.20	3.69



APPENDIX C
BED TOPOGRAPHY OF STUDY SITES

POST-RESTORATION SITE



Units of Bed Elevation are in meters.

APPENDIX D
2-D WSEL CALIBRATION

Calibration Statistics

% Nodes within 0.1'	Nodes	QI	Net Q	Sol Δ	Max F
76%	15234	0.31	0.47%	<.000001	2.99

Cross Section 2

Difference (measured vs. pred. WSELs)

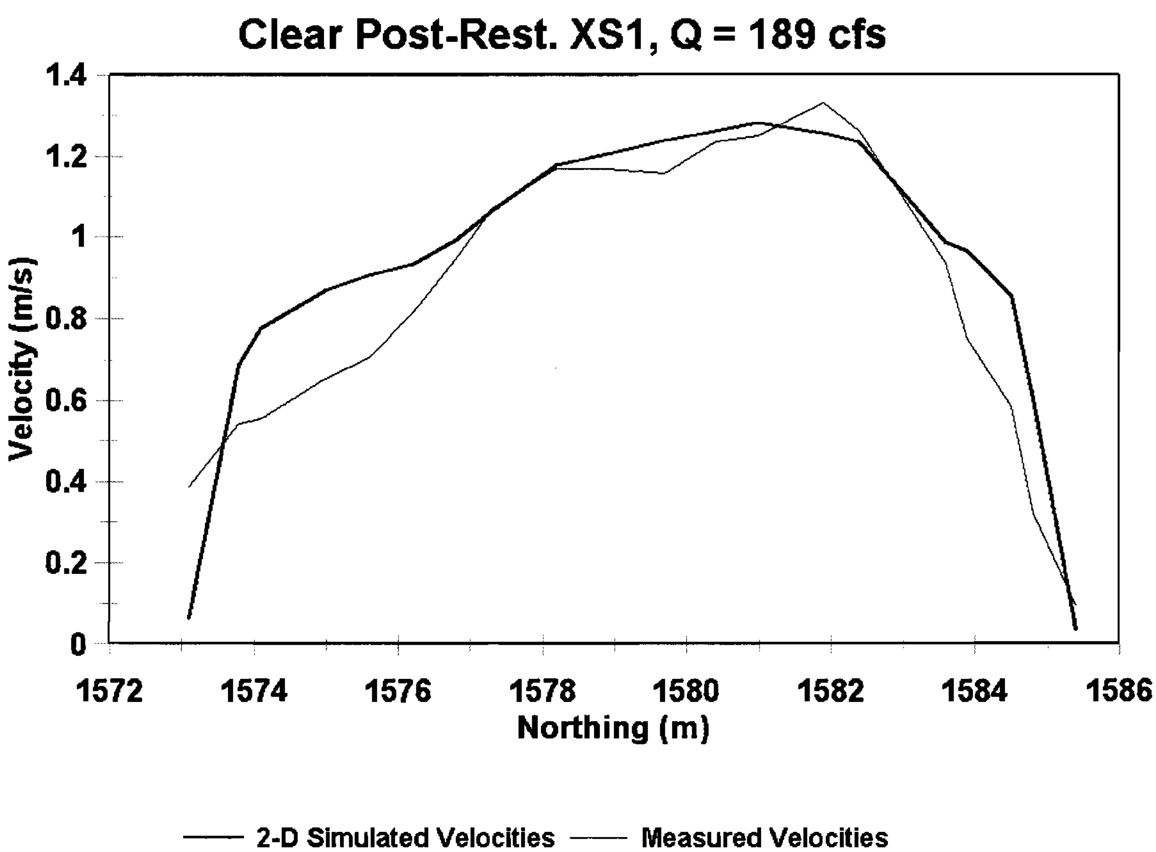
Br Multiplier	Average	Standard Deviation	Maximum
0.3	0.09	0.02	0.12

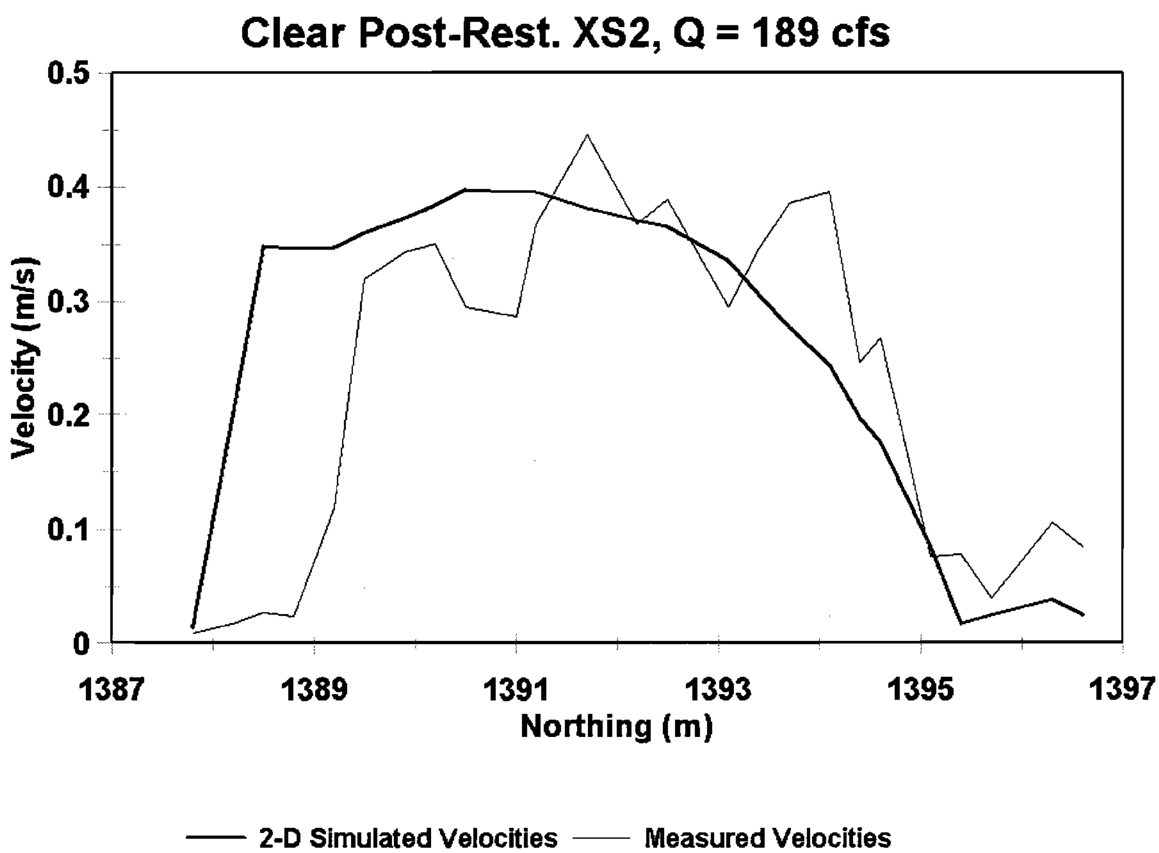
APPENDIX E
VELOCITY VALIDATION STATISTICS

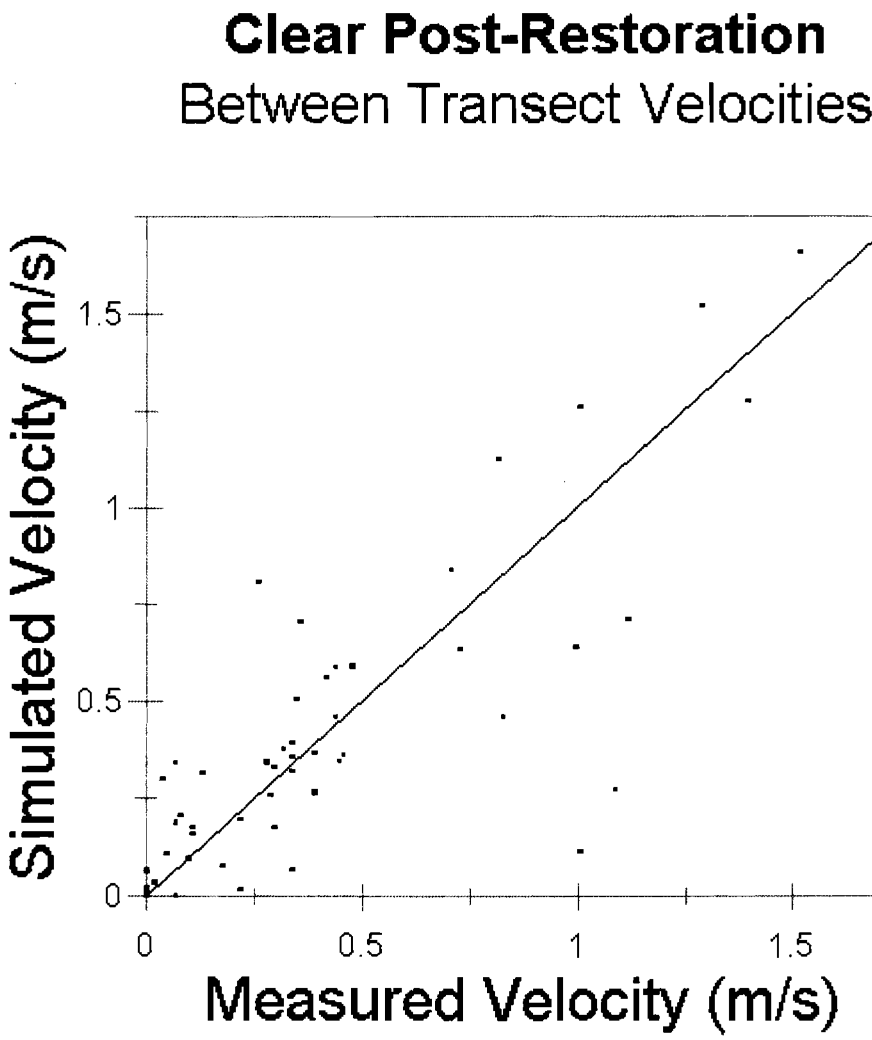
Difference (measured vs. pred. velocities, ft/s)

Measured Velocity	Number of Observations	Average	Standard Deviation	Maximum
< 3 ft/s	43	0.39	0.38	1.81
> 3 ft/s	10	45%	27%	90%

All differences were calculated as the absolute value of the difference between the measured and simulated velocity.




Clear Post-Rest. XS2, Q = 189 cfs
0.5
0.4
0.3
0.2
0.1
0
Velocity (m/s)
1387
1389
1391
1393
1395
1397
Northing (m)
2-D Simulated Velocities
Measured Velocities



Clear Post-Restoration
Between Transect Velocities
Simulated Velocity (m/s)
1.5
1
0.5
0
0
0.5
1
1.5
Measured Velocity (m/s)

APPENDIX F
SIMULATION STATISTICS

Post-restoration Site

Flow (cfs)	Net Q	Sol Δ	Max F
50	2.14%	.000003	1.38
75	1.43%	.000009	1.70
100	1.07%	.000004	1.57
125	0.86%	.000004	1.47
150	0.48%	.000004	1.59
175	0..60%	.000002	1.55
200	0.70%	.000003	1.77
225	0.94%	.000003	1.92
250	1.13%	.000001	2.00
275	1.03%	.000001	2.03
300	0.59%	.000003	1.77
350	2.42%	.000006	1.80
400	1.06%	.000006	1.70
450	1.02%	.000004	1.60
500	1.20%	.000002	3.21
550	0.90%	.000007	2.40
600	0.94%	.000008	2.42
650	1.58%	.000002	2.88
700	2.73%	.000003	2.77
750	3.44%	< .000001	2.66
800	2.95%	< .000001	2.48
850	0.41%	< .000001	2.69
900	0.47%	< .000001	2.99

APPENDIX G
HABITAT MODELING RESULTS

Fall-run Chinook salmon spawning WUA (ft^2)

Flow (cfs)	Pre-Restoration Total	Post-Restoration Plan	Post-Restoration 3A Site
50	751	9365	6652
75	1842	15586	9106
100	2716	21086	10764
125	2837	25198	11819
150	2964	25274	13078
175	3173	26404	14155
200	3663	26188	14735
225	4215	27588	14812
250	4963	26016	14348
275	5641	24499	13993
300	6292	22669	13789
350	7246	19246	13412
400	7929	16318	13466
450	8418	14079	12852
500	8475	12002	12023
550	8345	10753	11259
600	7884	9698	10656
650	7353	8751	10409
700	6631	7998	10075
750	6109	7287	9741
800	5559	6587	9440
850	4856	6071	8923
900	4182	5759	8310

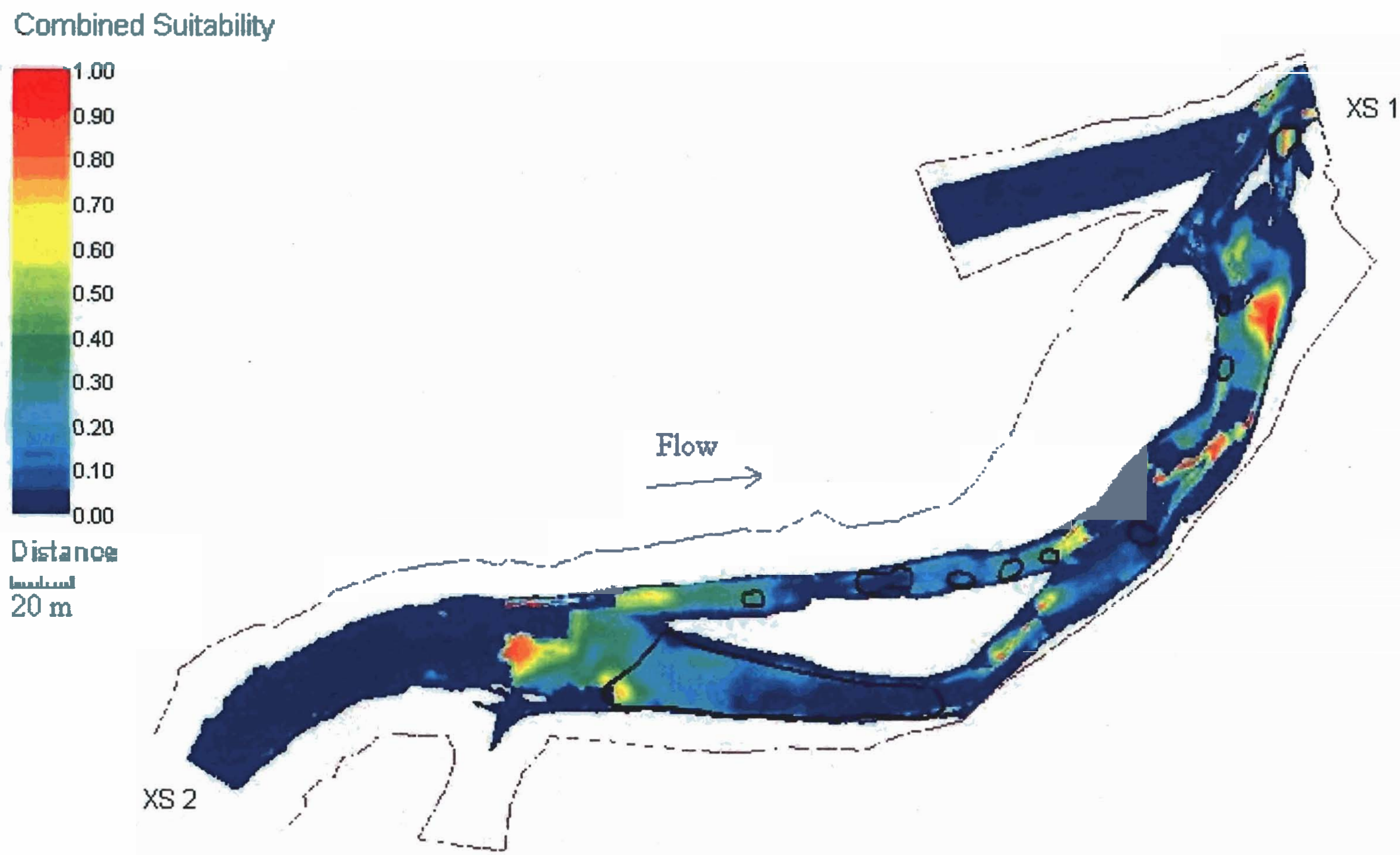
Fall-run Chinook salmon fry WUA (ft^2)

Flow (cfs)	Pre-Restoration Total	Post-Restoration Plan	Post-Restoration 3A Site
50	4933	7284	10,062
75	5789	6586	9654
100	6285	6179	9258
125	7170	5942	9014
150	7828	4807	8670
175	9102	4823	8244
200	9679	4734	8013
225	9570	6049	7908
250	9049	6164	7803
275	8995	6276	7626
300	8782	6367	7411
350	8117	6473	7040
400	8014	6344	6846
450	7673	6267	6588
500	7623	6488	6578
550	7632	6448	6571
600	7843	6555	6495
650	8104	6658	6313
700	8210	6691	6147
750	8168	6457	5938
800	8049	6634	5665
850	8011	6908	5592
900	7552	6839	5538

Fall-run Chinook salmon juvenile WUA (ft^2)

Flow (cfs)	Pre-Restoration Total	Post-Restoration Plan	Post-Restoration 3A Site
50	594	1618	1751
75	749	1628	1906
100	846	1566	1905
125	1127	1503	1826
150	1263	1205	1825
175	1707	1239	1807
200	1976	1264	1803
225	2008	1600	1814
250	2169	1691	1837
275	2226	1827	1831
300	2276	1887	1798
350	2230	2094	1765
400	2157	2245	1757
450	2125	2176	1746
500	2069	2035	1756
550	2107	2038	1749
600	2099	1990	1742
650	2045	1959	1697
700	2062	1948	1690
750	2082	1888	1642
800	2072	1970	1560
850	2045	2040	1473
900	1981	2065	1417

APPENDIX H
COMBINED HABITAT SUITABILITY OF REDDS



Combined Suitability
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Distance
20 m
Flow
XS 1
XS 2